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TO : The Files - Contract 111-13224-9

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SUBJECT: Trip Report - Development of BC-13 Thermoelectric Generator

1. On 21 September 1959 a trip was made to [redacted] to monitor progress of the 10-watt thermoelectric generator under Contract 111-13224-9. Present at the discussions were:

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2. The contractor has completed fabrication of a test model of the BC-13, which has 101 thermocouples connected in a series-parallel to give an open circuit voltage of 22.5 volts with a temperature difference of 1,000°F. The maximum output of this generator is approximately 9 watts into a matched resistive load. The overall performance of this model is satisfactory and the contractor will make delivery of the BC-13 around 1 November 1959. After a series of tests on this model and a second model, the contractor will build a third unit for delivery.

3. The BC-13 will have two equal output voltages which can be used for charging 6 or 12-volt batteries. In addition to the generator itself, there will be provisions for connecting a portable propane tank, a five-foot hose to connect it with a larger propane tank such as used in house trailers, and an indicating device to indicate maximum output. This indicating device will simply be a voltmeter with a yellow-green-red face to indicate proper operating range. The propane burner in the generator is a removable device and very easily cleaned. This burner has a capability of giving a hot junction temperature of 1,170°F. The cold temperature varies depending upon ambient temperatures, but runs around 160°F. The generator is approximately 10 inches in diameter, including the radiated fins, and approximately 10 inches high. The total weight of the unit will be approximately 15 lbs., not including the propane tank.

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SUBJECT: Trip Report - Development of BC-13 Thermoelectric Generator

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Attachment:
Thermofax Copy of Performance and Environmental
Test Results of SNAP-III

cc: R+D Subject Files
R+D Lab
SPS/AF
OC-T/CT/OR
Monthly (2)
EP Chrono

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File Copy

Snap III

Performance Data and Environmental Test Results of SNAP III

Fred N. Huffman and Louis W. Gross*

The polonium fueled SNAP III thermoelectric generator displayed on President Eisenhower's desk on January 16 of this year has produced electrical power continuously for over 5000 hrs and is still operating on the original fuel charge. A second polonium-fueled unit, which powered an amateur radio station at The Atom Fair in April, has also run continuously and without incident until the present time. These operating times are a testimonial to the longevity and reliability of the device.

SNAP III was developed by The Martin Company in conjunction with Minnesota Mining and Manufacturing Company and Mound Laboratory. It is part of the Subsystem for Nuclear Auxiliary Power demonstration program for radioisotopic fueled thermoelectric and thermionic converters sponsored by the Missiles Project Branch of the Atomic Energy Commission.

The detailed design problems and constructional features of SNAP III have been discussed in Refs. 1 and 2. However, a brief description of the generator provides a useful background for the data and test results to be presented. An artist's concept of the generator is shown in Fig. 1. The center cylinder represents the polonium radioisotope fuel capsule which is contained in the molybdenum block. Surrounding the heat source are 54 semiconductor thermoelectric elements making up 27 thermocouples. Each thermocouple consists of a P-type sodium doped lead telluride leg and a N-type iodine-doped lead telluride leg placed in electrical series and in thermal short. Iodine doping is used in place of the original bismuth doping for reasons of quality control. Each leg is made of two differently doped segments so that each operates with maximum effectiveness within its temperature range. A fraction of the radioisotopic heat flows through the lead telluride elements and is converted into electrical power. The details of the generator construction can be seen best in Fig. 2. The cold junction electrical connection is soldered while the hot junction electrical and thermal continuity is maintained by a compressive spring-loaded contact. The action of the spring pressure and temperature is such that the lead telluride is partially fused to the hot shoe. This technique gives electrical continuity even though sublimation may take place from the hot junction area.

*This work was sponsored by the AEC under Contract No. AT(30-3)-217.

A detailed weight breakdown is given in Table 1. Obviously, there are many ways of reducing the generator weight by reducing the weights of individual components as well as by overall geometrical and detail redesign. A straightforward redesign should double the watt/pound rating of the present unit.

TABLE 1

Component Weights of SNAP III

	(gm)
Insulation	120
Case	490
Cold Junction Housing	338
Heat Source	192
Thermocouple Elements	286
Hot Shoes	43
Cold Junction Socket	117
Springs, Screws and Washers	73
Element Cap (pair and wire)	111
	1,770
Assembled Weight	1,850 gm (4.08 lb)

The initial characteristics of the second polonium-fueld SNAP III are tabulated in Table 2 for both room ambient and simulated space conditions. Figure 3 gives a plot of the corresponding power out versus load resistance data. Note the reduction in output (and efficiency) due to the increase in cold junction temperature in the vacuum environment. No claim is made that the bell jar arrangement simulates space conditions accurately. However, it does indicate the relative difference in performance between room ambinet and space conditions.

Instrumental errors and errors due to non-equilibrium temperatures probably average three per cent. Data from a given generator reproduce fairly well, but units may vary in thermoelectric properties and electrical and thermal contact resistances such that overall efficiencies differ as much as ten per cent. Also, the data cover several different generators which were constructed with different insulators. Thus, all the electrical performance data in this paper should be regarded as typical rather than precise.

TABLE 2

Initial Characteristics of Second Po-210 Fueled SNAP III

	Room Ambient	Bell Jar
Polonium-210 thermal input, w	50.2	50.2
Electrical output (3 ohm load), w	3.40	2.92
Output potential, v	3.20	2.95
Overall efficiency, %	6.78	5.82
Hot junction temperature, °F	900	950
Cold junction temperature, °F	173	223
Weight, lb	4	4
Height, in.	6	6
Diameter, in.	4.8	4.8
Internal generator pressure, mm Hg, Argon-Methane	200	200
Dose rate at 1 meter, mrem/hr	3.5	3.5

Some confusion exists as to what SNAP III is. SNAP III is a rugged prototype unit which has operated reliably for long periods. It has a measured efficiency of 6.8% in room ambient conditions and a measured efficiency of 5.8% in simulated space conditions. Although one may squeeze five watts out of the generator in room ambient conditions, it is, in general, a 2.5-w unit in a space environment. Although SNAP III is far from the ultimate in direct conversion power supplies, it does represent available hardware capable of power densities of 2/3 w/lb and energy densities of 1000 w hr/lb. The generator incorporates years of Minnesota Mining and Manufacturing Company experience with lead telluride thermoelectric elements for gas burner controls. Fabrication techniques and detail design have been refined in the process of building a total of eight SNAP III units. Two of these units have been loaded with isotopic fuel and other electrically heated models are undergoing test programs.

To truly optimize an isotopic thermoelectric space system, many parameters must be specified. Exact material properties of the thermoelectrics and the insulation must be known. Electrical and thermal contact resistances are needed. The electrical load profile and regulation, mission lifetime, orbit data, structural tie-in to vehicle, vehicle temperature, and operating radiation shield requirements must be specified. Isotope availability, cost, development time and ground handling considerations impose constraints on the design. Hazard considerations of launch abort and reentry also reflect on the design. The controlling optimization parameter (such as, energy density, efficiency, cost, size) must be determined.

Unless these items are established, an analytical optimization is futile. Obviously, many of these items are a matter of engineering judgement and involve political as well as technical considerations. One should keep in mind that an optimization is seldom better than its weakest assumption.

It is interesting to note that in the present unit, the weight of the thermoelectric material is less than 10% of the total generator weight. Although optimization might increase this percentage somewhat, it is indicative of practical designs. Clearly, designs which optimize on the basis of thermoelectric material weight are likely to be fallacious.

Analysis of thermoelectric generator performance in terms of Seebeck voltage, resistivity, and thermal conductivity have been given in a number of references (Refs. 3 and 4). However, SNAP III performance will be discussed in terms of heat balance. Assuming Thompson effects are negligable.

$$P_{isotope} = K_{TE} (T_H - T_c) + K_{Ins} (G,P)(T_h - T_c) + \pi I - \frac{1}{2} r I^2$$

G = generator fill gas (i.e. hydrogen or argon-methane)

π = Peltier coefficient

where:

I = current

T_h = hot junction temperature

T_c = cold junction temperature

P = internal gas pressure

The interaction of these terms accounts for the performance of the device. The effect of the generator fill pressure is shown in Fig. 4. A typical volt-ampere curve is shown in Fig. 5. The effect of Peltier cooling on the hot junction as a function of load resistance is illustrated. The upper and lower crosses correspond to hot junction temperatures of 1000 and 900°F, respectively. The slight non-linearity is the combined result of Peltier cooling and shifting of the figure of merit with a change in hot junction temperature.

A study of electrical power output in a bell jar versus a load resistance parametric in thermal power for vacuum and one atmosphere fill pressure is shown in Figs. 6 and 9 for two SNAP III configurations. These generators are identical except that in the one design the diameter of the thermoelectric element is reduced to increase the efficiency at lower power inputs by increasing the hot junction temperatures. For space conditions, the higher power generator may be rated at around 2.5 w and the lower power unit at 1.5 w. Note that a hot junction temperature constraint of 1100°F is used for an atmosphere of reducing gas fill pressure and a constraint of 900°F for the evacuated condition. These values are selected to give generator lifetimes of over a year. For shorter missions both constraints could be relaxed somewhat. The reducing atmosphere not only protects the thermoelectric elements from oxidation but also decreases the sublimation rate of lead telluride.

All of these data were taken in a bell jar with the generator resting on an insulated tripod. A circuit was provided for automatically switching load resistances, and readings of load voltage, open circuit voltage, and short circuit current were taken at each equilibrium point.

For a given generator internal fill pressure condition and load resistance, a crossplot of power output versus power input with isotope power input versus time will give a good indication of the performance of SNAP III in a space environment. These data may be summarized for a given load resistance as shown in Figs. 10 and 11. These bell jar results may be compared with the room ambient data plotted in Fig. 12. Obviously, operation in a space environment seriously decreases the generator's performance. For high efficiency, the desirability of having the generator evacuated is apparent.

A difficulty in dealing with isotopic-fueled generators is that the thermal input varies exponentially with time such that after a specified time lapse, called the half-life, the thermal output is one-half of its initial value. This makes the generator design awkward in two respects. First, the output power varies with isotope power input and, second, the end of life efficiency is much less than the original efficiency.

The usual mission requires a constant electrical power into a fixed load (averaged over a day) for the life of the mission (usually about the isotope half-life). For instance, assume that the mission requires an electrical output of 0.80 w, for the half-life of the isotope fuel (138 day Po-210, 156 day Cm-242 or 275 day Ce-144). From Fig. 11, it is seen that a thermal input of 19 w is needed at the end of life for the vacuum case or thermal input of 26 w for one atmosphere case. Therefore, the initial fuel charge would appear to be 38 and 52 thermal watts for the vacuum and gas-filled cases, respectively. However, an initial input of 38 w would exceed the hot junction temperature constraint in the vacuum case and make this mode of operation, alone, impossible. Consider the case where the generator is initially filled with an atmosphere of reducing gas and loaded with a thermal input of 38 w. Ample output would be available initially but would be reduced to 0.35 w at the end of a half-life. This mode of operation, alone, does not meet the requirements. However, if the generator fill pressure is properly programmed from one atmosphere initially to vacuum at the end of life, the electrical output requirement is met and the mission has been accomplished with 14 fewer thermal watts than in the simple one atmosphere case. This represents a fuel investment saving of over one-third. Because of the extreme expense of isotope fuel, this economy is, in general, worth the design effort. In addition, an incidental result is that the electrical output is flattened by this procedure.

This technique allows the generator design to be optimized for maximum efficiency at the end of life (usually about a half-life) without exceeding thermoelectric material operating temperature with an initial charge of fuel. Sometimes the misnomer, "power flattening" is given to this feature instead of the more descriptive term, "heat dumping". It should be kept in mind that the thermal short is primarily an isotope economy measure and that the power flattening is merely an extra dividend.

Heat dumping will also increase the watt/pound rating of the generator.

Several methods of achieving a variable thermal short for this purpose have been suggested. A method that looks promising with the SNAP III generator is that of variable generator fill pressure. A typical effect on hot junction temperature is shown in Fig. 4. Analysis of the data indicate that almost full half-life control is possible by considering the effect of pressure on heat leakage and hot junction constraints. Unless a heat dump mechanism is used, Fig. 10 shows that the evacuating of the SNAP III generator and limiting the hot junction temperature to 900°F with an initial isotope loading of 47 w is equivalent in electrical output to filling the generator with an atmosphere raising the hot junction to 1100°F and using an initial load of 65 w. (Note: Peltier cooling of the hot junction also aids in packing in more thermal power initially.) The power flattening due to heat dumping is also shown. Work is under way at Martin to accomplish this. It is interesting to note that the generator was not designed with this feature in mind. Again, the pressure data should be considered as typical rather than exact because of significant variations among generators as to thermal contact resistances when the gas film conduction across junctions is removed by evacuating the generator. The loss of film conduction results in greater thermoelectric element temperatures for a given power input and is reflected in poorer performances.

The thermal insulation in the hemispherical domes is compressed Min-K, 1301. The 5% material has a compressive strength of 200 psi. Powdered Min-K surrounds the elements themselves and is compacted by vibration during assembly.

Thespring force on an individual element at room temperature is approximately 2.2 lb and increases to about 5.1 lb at 1100°F. The adjusting screw has a thread pitch of 20 threads/in. and a spring rate of 175 lb/in. The screw is set 1/3 turn from the free length of spring. These tension parameters vary with mission.

The dynamic tests to be discussed were in accordance with specifications submitted by Jet Propulsion Laboratory. A detailed report of these tests will soon be available in Ref. 5.

The vibration test utilized a Calidyne vibration system Model No. 177A. The test program consisted of a sinusoidal vibration of 5 g rms from 15 to 1500 cps, superimposed on a random signal of 5 g rms, band-limited between 15 to 1500 cps for 5 min. The second portion of the tape consisted of a sinusoidal vibration of 8 g rms from 500 to 1500, superimposed on a random signal of 5 g rms, band-limited between 15 to 1500 cps for 5 min. Two test cycles were conducted in each of the three orthogonal planes shown in Fig. 13.

The frequency response of the shaker, mounting plate and test fixture was equalized by use of the system equaliser and a peak notch filter. Kronhite band pass filters were used to bring the relative level down 3 db at 1500 cps and 8.5 db at 15 cps. The generator in its fixture and mounted on the Calidyne vibrator is shown in Fig. 13. A typical equalization curve is given in Fig. 14.

Prior to each test, the generator was allowed to reach an equilibrium (room ambient) power input, power output, and hot junction and cold junction temperatures. These parameters were monitored throughout the tests.

The vibration tests showed only a small drop in efficiency in the x and z planes. The largest effect was in the y plane and is shown in Fig. 15. Note that the efficiency drop is constant after reaching its maximum until the vibratory force is discontinued. In every case, the generator completely recovered its original output within 10 min. In the worst case of the y plane, the efficiency was decreased only 0.3%.

Monitoring of the 2.80 d-c output showed a small ripple in the x and z plane which tripled in the y plane. Investigation of the ripple component revealed that the ripple frequency matched the shaker frequency. A sinusoidal vibration of constant 2 g rms from 15 to 1500 cps was applied in the x, y and z planes. The ripple component was constant in the x and z planes but peaked sharply at 700 cps in the y plane.

The acceleration test was conducted on a Genisco Accelerator. Oscillograph records show no observable change in any generator parameter. Test results are plotted in Fig. 16.

Shock test specifications called for four shocks in each plane with an input force of 50 g in a one millisecond rise time with no requirements on the rate of decay of the pulse. Accelerometers were mounted on the fixture such that the input and response accelerations could be monitored. The shock test results are similar to the vibration results. Again, the y plane data showed the largest ripple component and a decrease in efficiency. These data are plotted in Fig. 17. The electrical heating element, used to simulate the radioisotope, failed in the third shock in the y plane. The element was replaced and the shock tests completed.

Four SNAP III generators have passed complete vibration, acceleration and shock tests. In no instance has there been a failure of any component other than the electrical heater. Additional generators are presently undergoing test to improve the statistical significance of these results.

What are the design features of SNAP III that make it so rugged? One might expect that the spring-loaded construction would adequately cushion radial loads provided the spring resonances are not excited. Spring resonance does not turn out to be a problem because it lies much higher in frequency range than the vibration inputs. Packing the lead telluride elements in powdered Min-K insulation tends to dampen out any vibration on the part of the elements, themselves. All voids in the generator are filled with powdered Min-K so the generator can be regarded as a plastic solid. The axial support might be a subject of concern since it is maintained only by spring pressure of the individual elements on the heat source cylinder and the compressed Min-K domes. This apprehension is confirmed to some extent because of the consistently larger effects in the y plane tests.

The mechanism of power output decrease and its subseqnent recovery has yet to be explained. To do this, consider in detail the nature of the electrical contact at the hot junction. Under operating temperatures, the spring pressure causes plastic flow of the lead telluride to produce a partial mechanical bond to the hot junction shoe. The most likely explanation of the small decrease in efficiency during shock and vibration is that the contact resistance of the partial bonded contact increases with the simulated launch loads. After the test cycle, heat and pressure again fuse the hot junction contact and the generator output recovers completely.

Although these tests indicate that SNAP III generators will survive rocket launch, additional testing is underway to demonstrate integrity of isotopic power sources in case of launch abort and in reentry. For space applications, any of several other isotopic fuels under study will probably be substituted for Po-210.

Radiation damage of the thermoelectric material by gamma rays is being investigated. A couple similar to those in SNAP III has been irradiated for over 400 hr in Co-60 fields of 1.6×10^5 r/hr. A temperature gradient is being maintained in the test and no change in output has been observed.

In summary, although SNAP III was designed primarily as a proof of principle device, the electrical performance data and the vibration, acceleration and shock test results discussed indicate the feasibility of using the present generator for extending the useful life of satellites.

References

1. Barmat, M., Anderson, G.W., and Bollmeier, E.W.; "SNAP III - Electricity from Radionuclides and Thermoelectric Conversion", Nucleonics, Vol. 17, No. 5, 1959

2. Fritts, R.W.; "Design Parameters for Optimizing the Efficiency of Thermoelectric Generators Utilizing P-type and N-type Lead Telluride", June 24, 1959, AIEE Transactions

3. Ioffe, A.F.; "Semiconductor Thermoelements and Thermoelectric Cooling", Infosearch, London

4. Bollmeier, E.W.; "An Elementary Design Discussion of Thermoelectric Generation", Paper No. CP 59-937, 1959

5. Gross, L.W.; "Environmental Test", SNAP III Generator, MND-P-2101

List of Figures

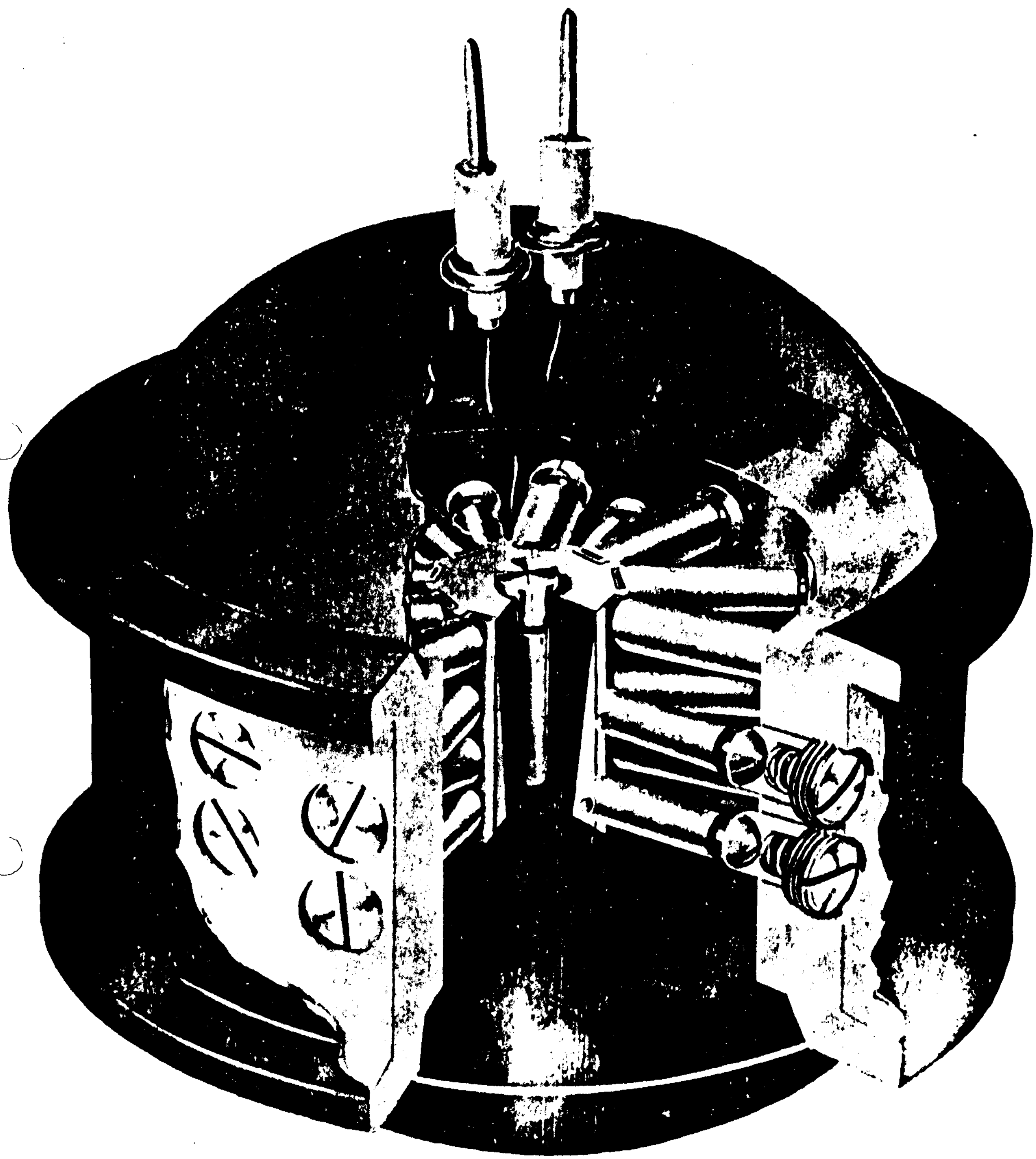

Fig. 1. Artist's Concept of SNAP-III Generator

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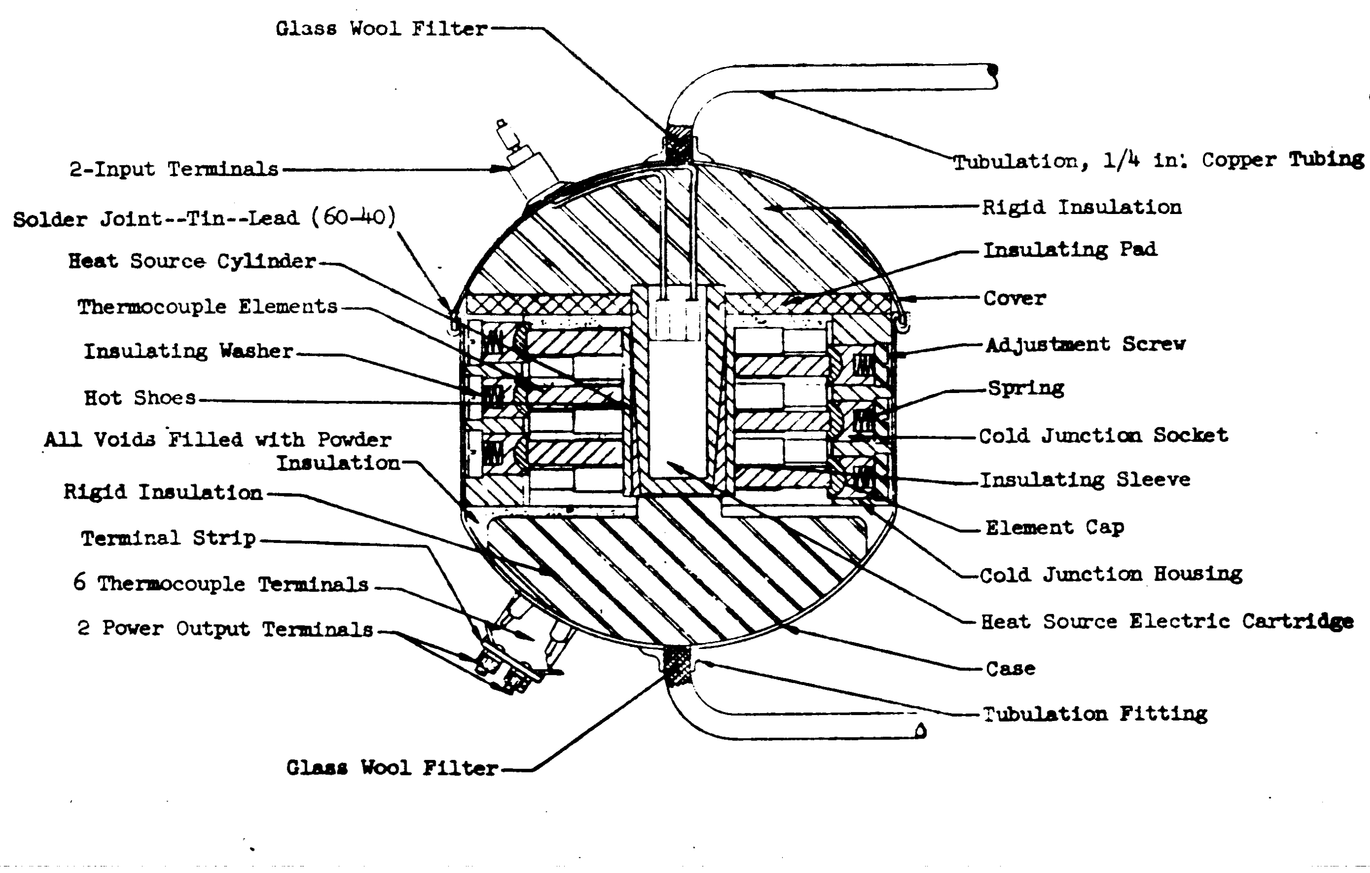

Fig. 2. Cross-Sectional View of SNAP-III

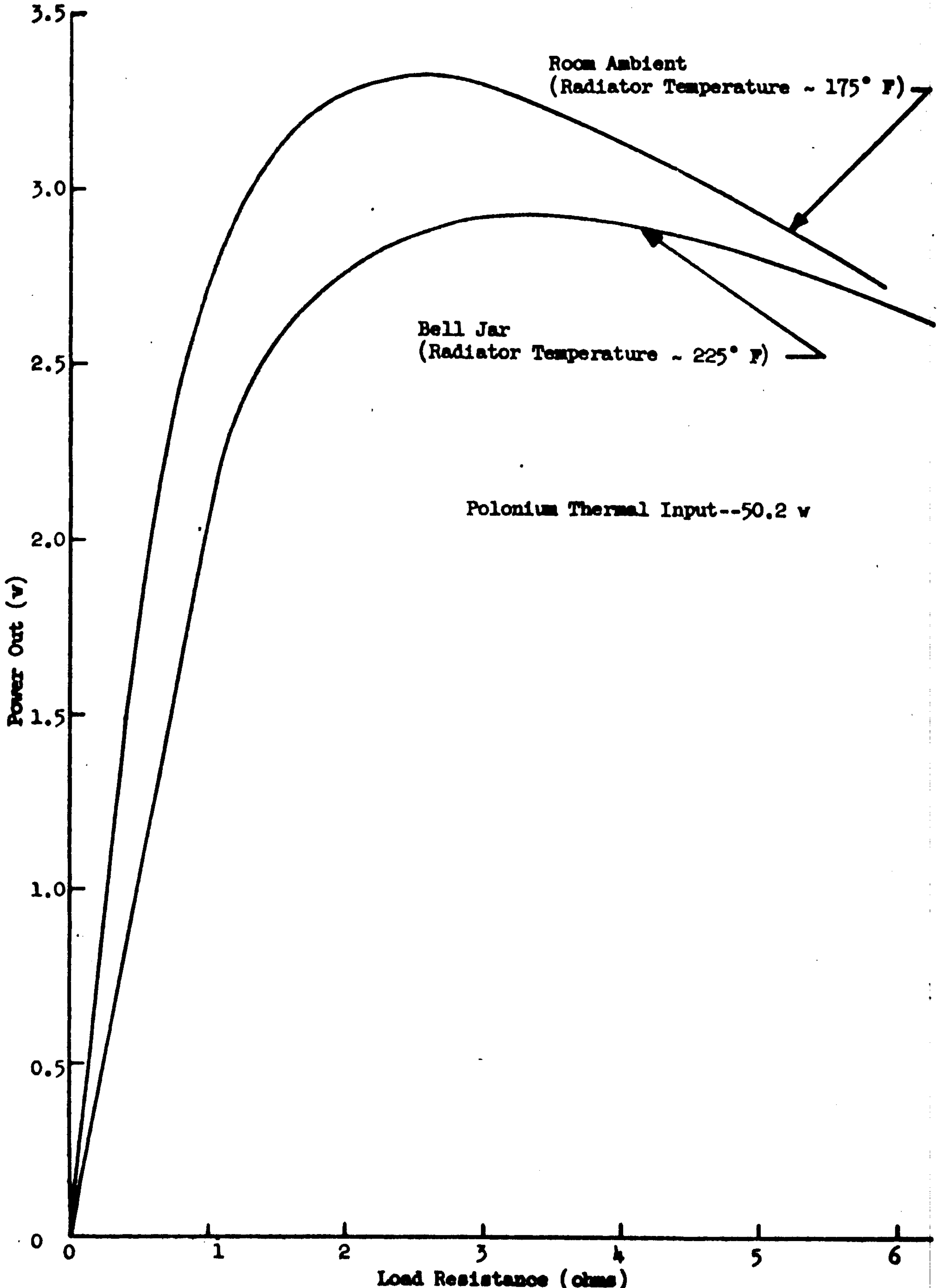

Fig. 3. Power Output vs Load Resistance for Second Po-210 Fueled SNAP-III

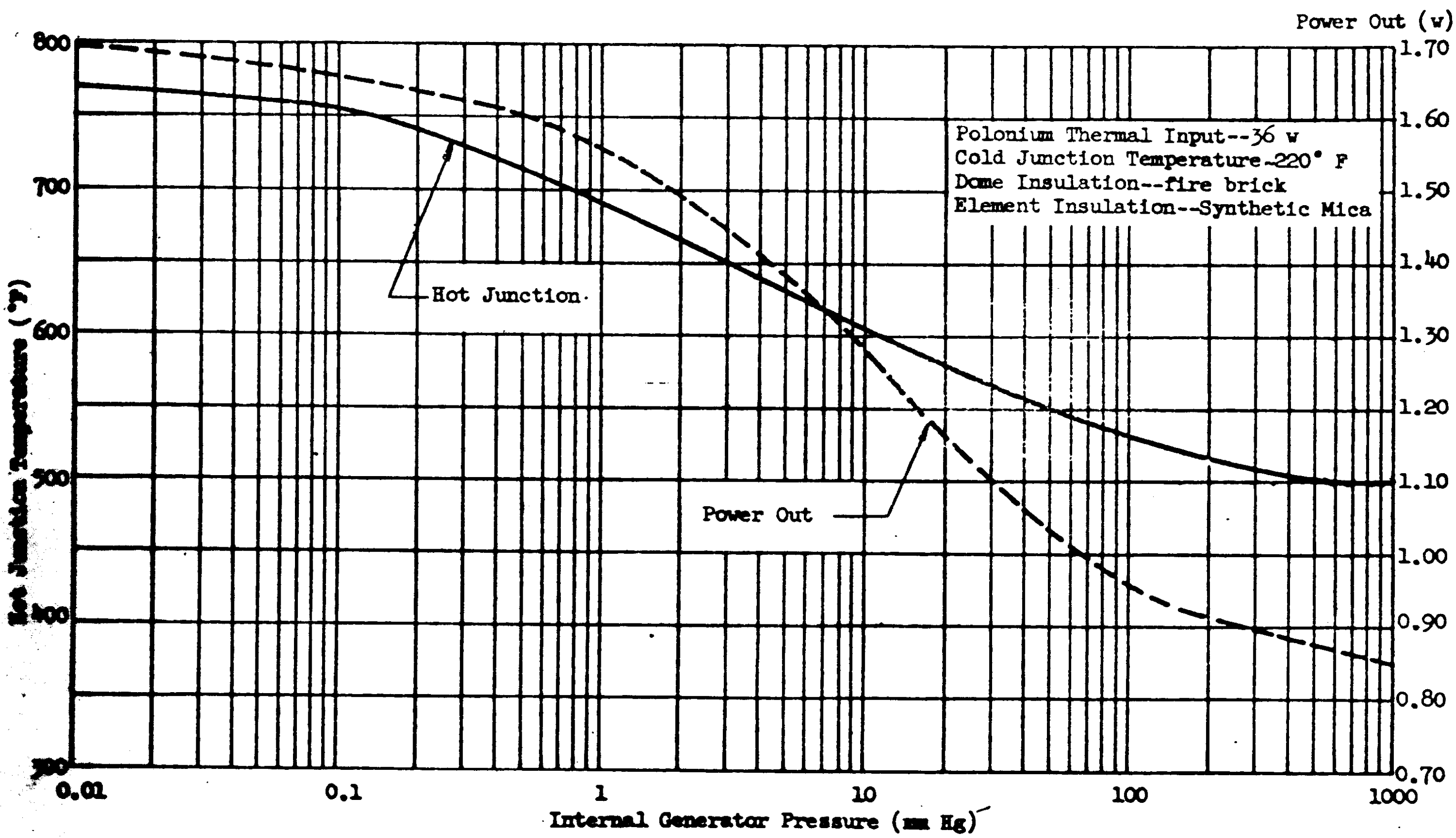

Fig. 4. Electrical Output and Hot Junction Temperature [illegible]

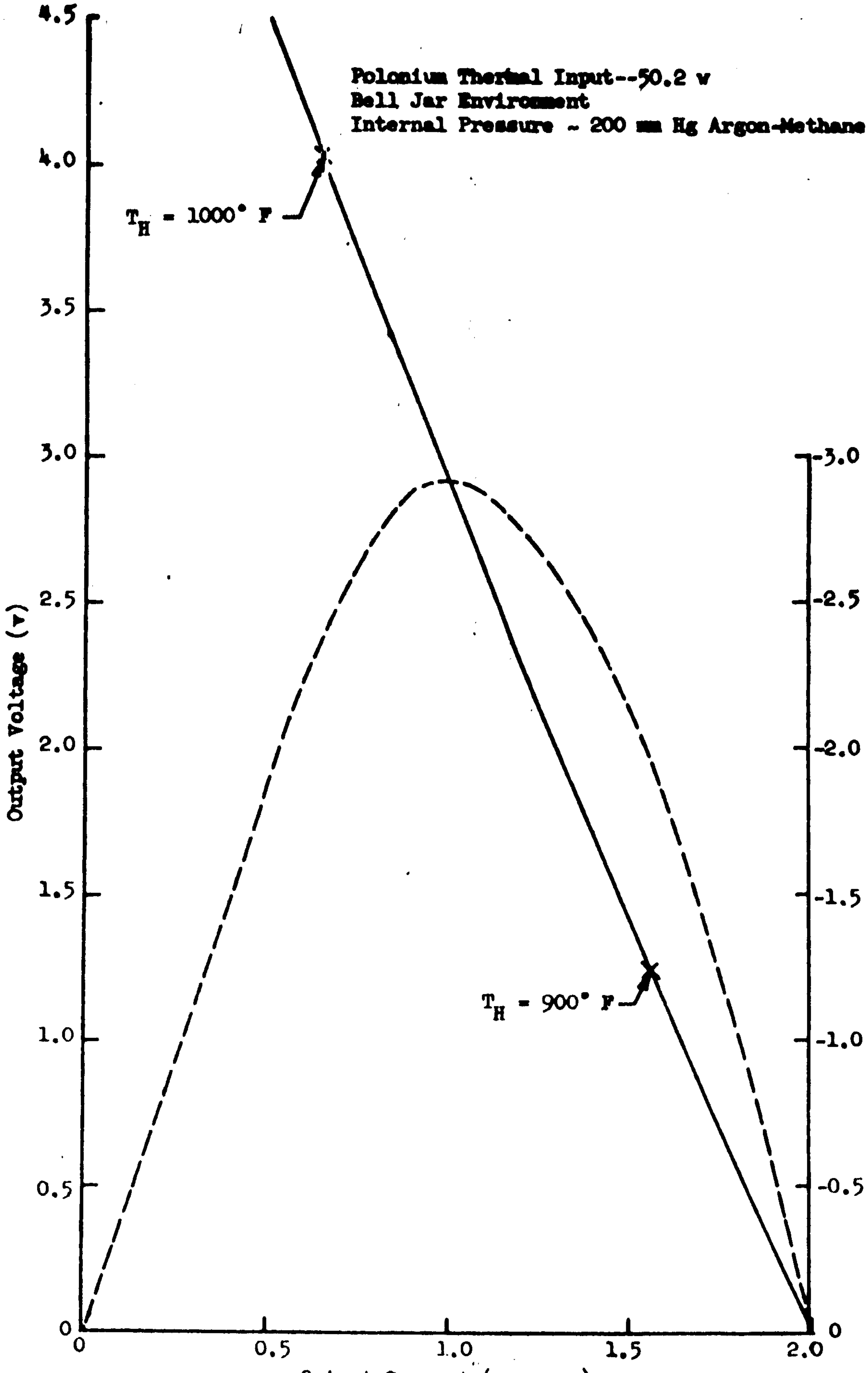

Fig. 5. Volt - Ampere and Power Output Curves for Second Po-210 Fueled SNAP-III

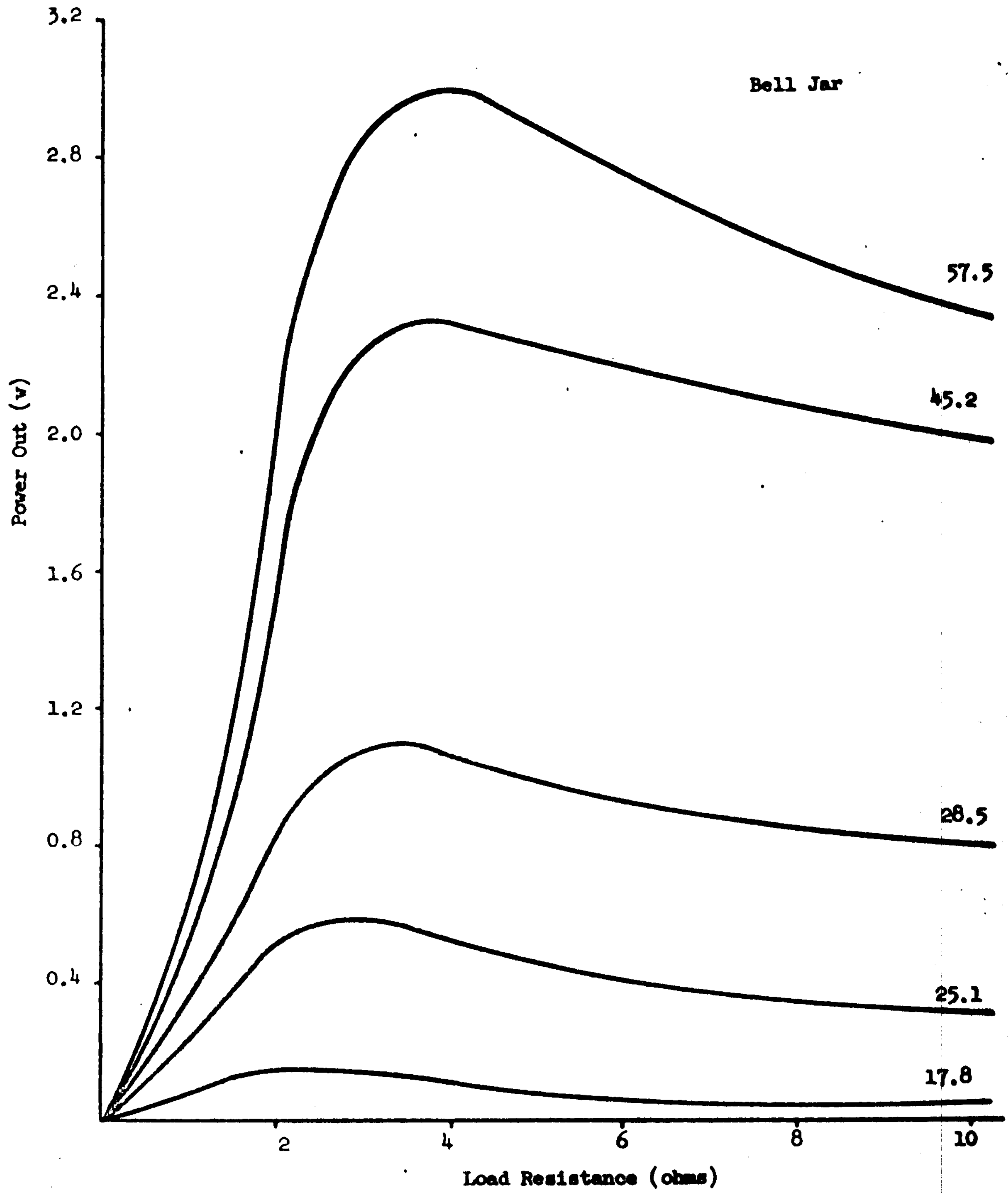

Fig. 6. Power Out vs Load Resistance Parametric in Power In (SNAP-III Filled With Atmosphere 85% He--15% H)

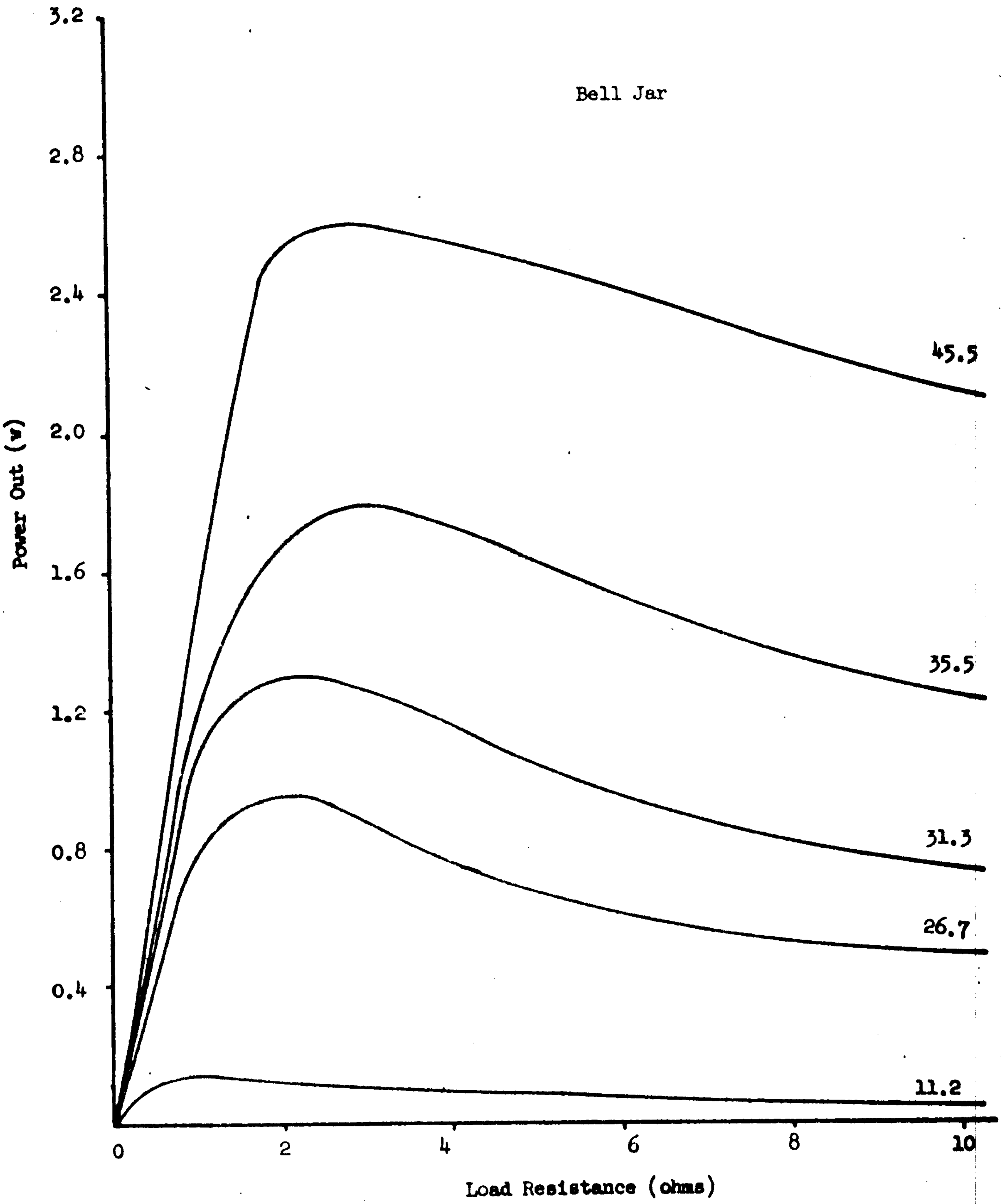

Fig. 7. Power Out vs Load Resistance Parametric in Power In (SNAP-III Evacuated)

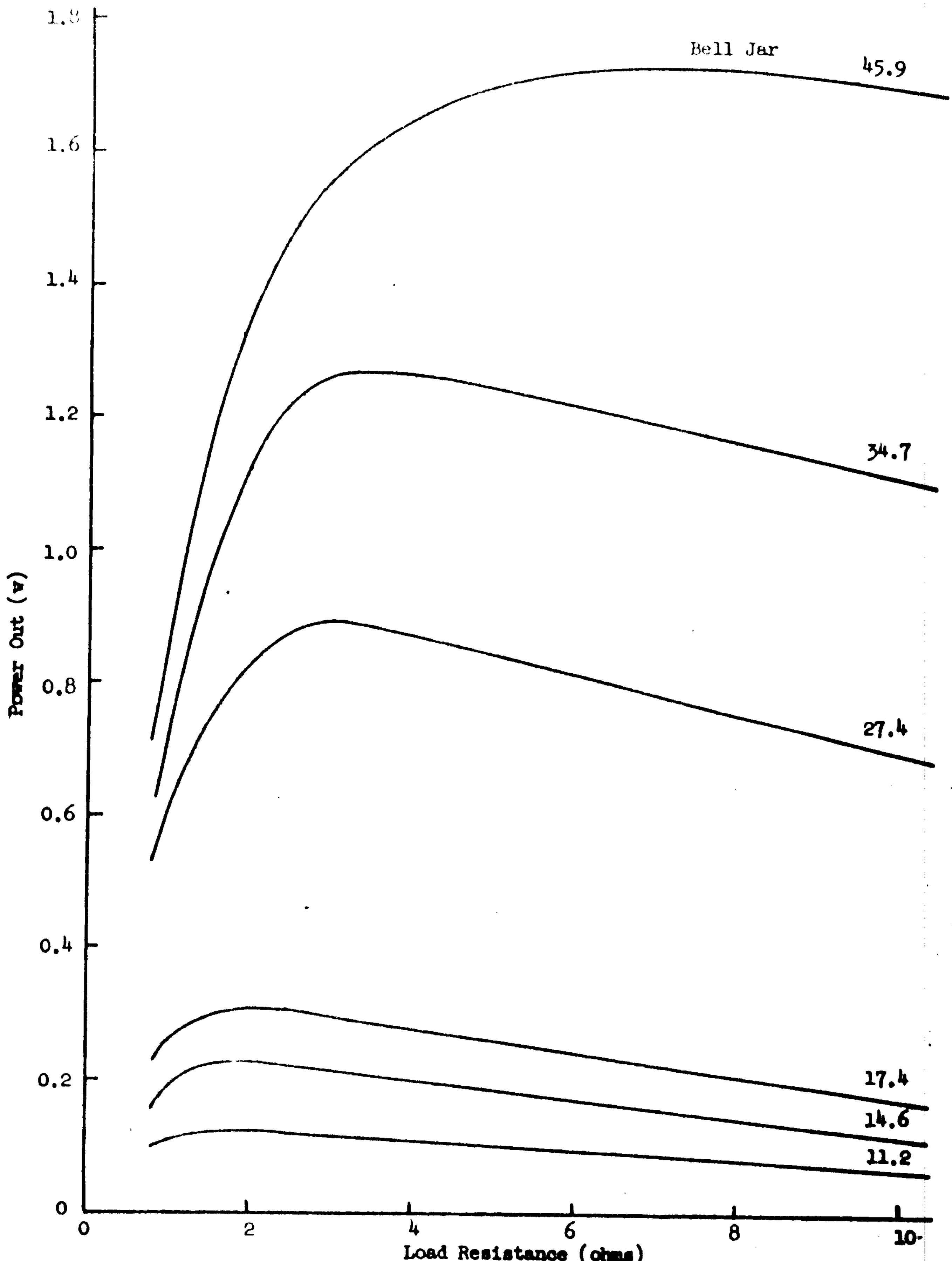

Fig. 8. Power Out vs Load Resistance Parametric in Power In (Low Power SNAP-III With Atmosphere of 95% A--5% H)

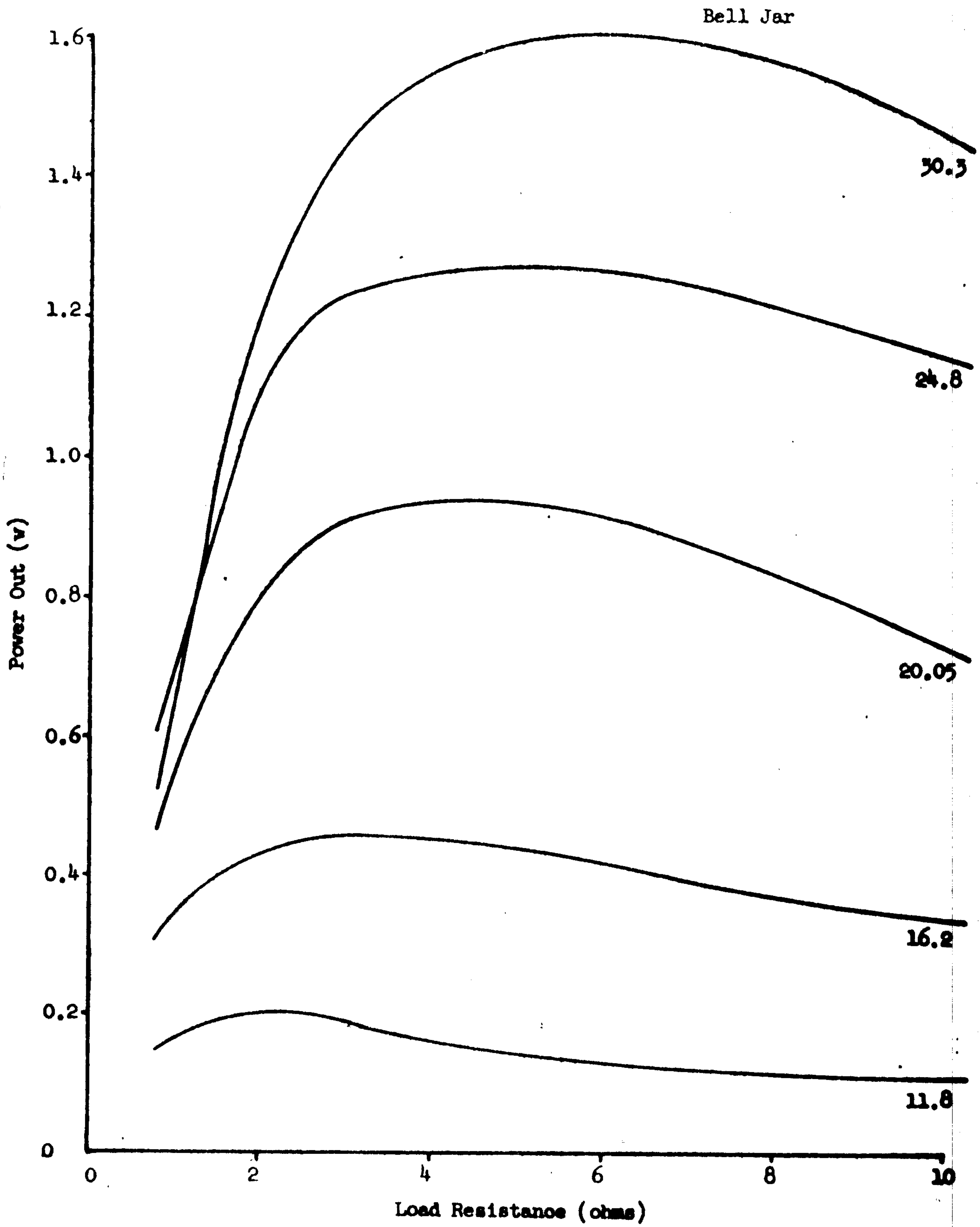

Fig. 9. Power Out vs Load Resistance Parametric in Power In (Low Power SNAP-III Evacuated)

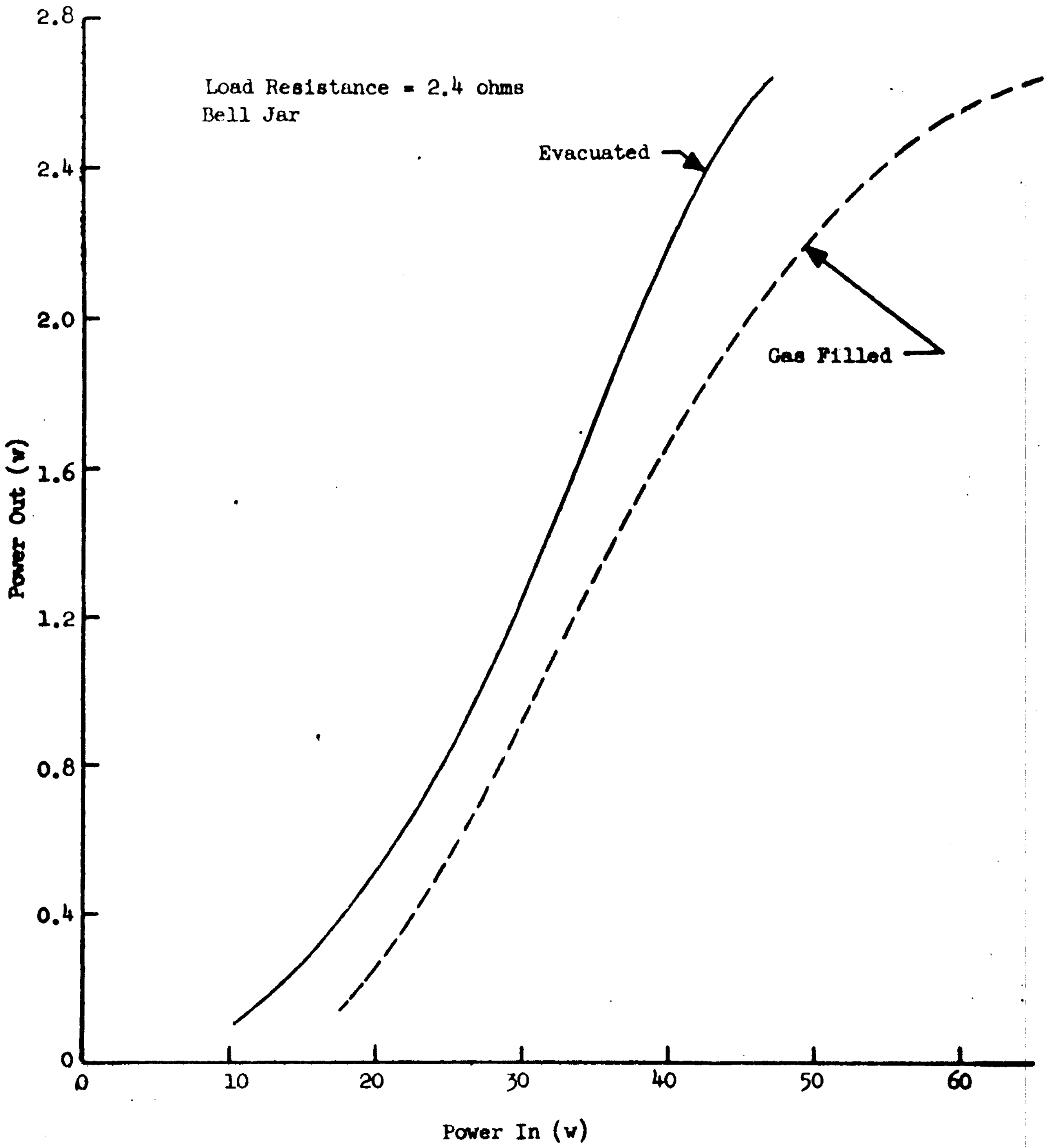

Fig. 10. Power Out vs Power In for SNAP-III Evacuated and Gas Filled Conditions

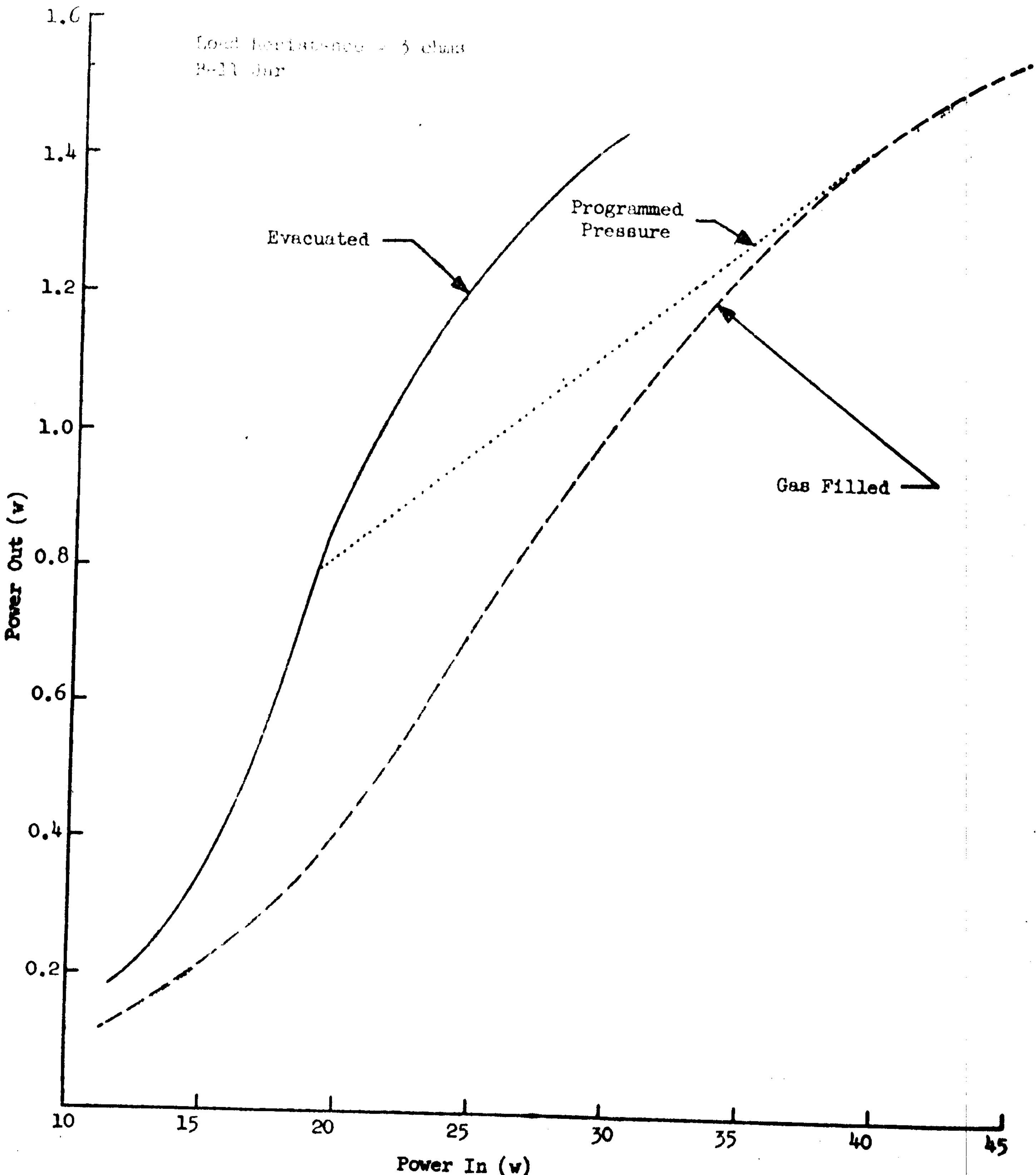

Fig. 11. Power Out vs Power In for

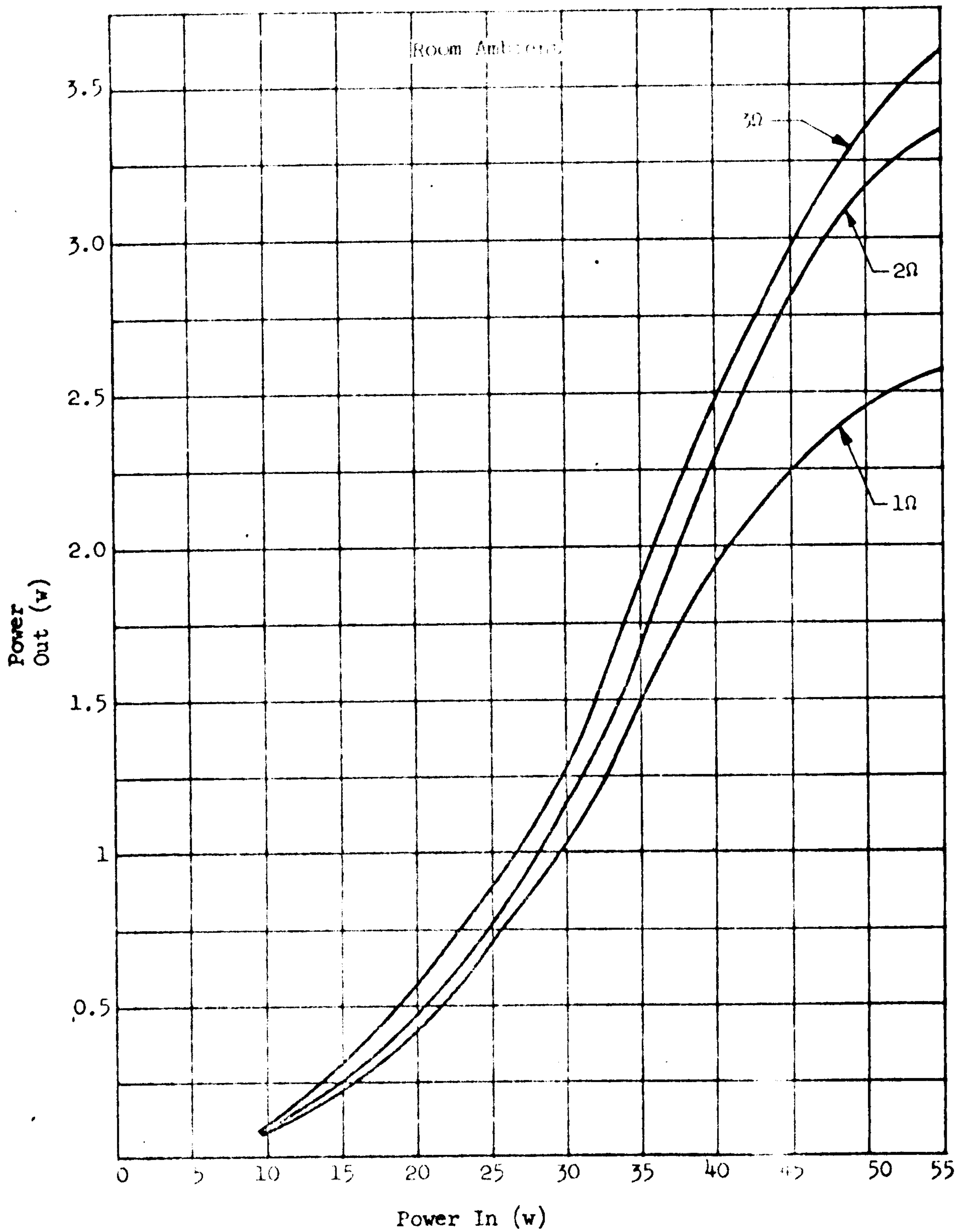

Fig. 12. Power Out vs Power In for Evacuated SNAP-III

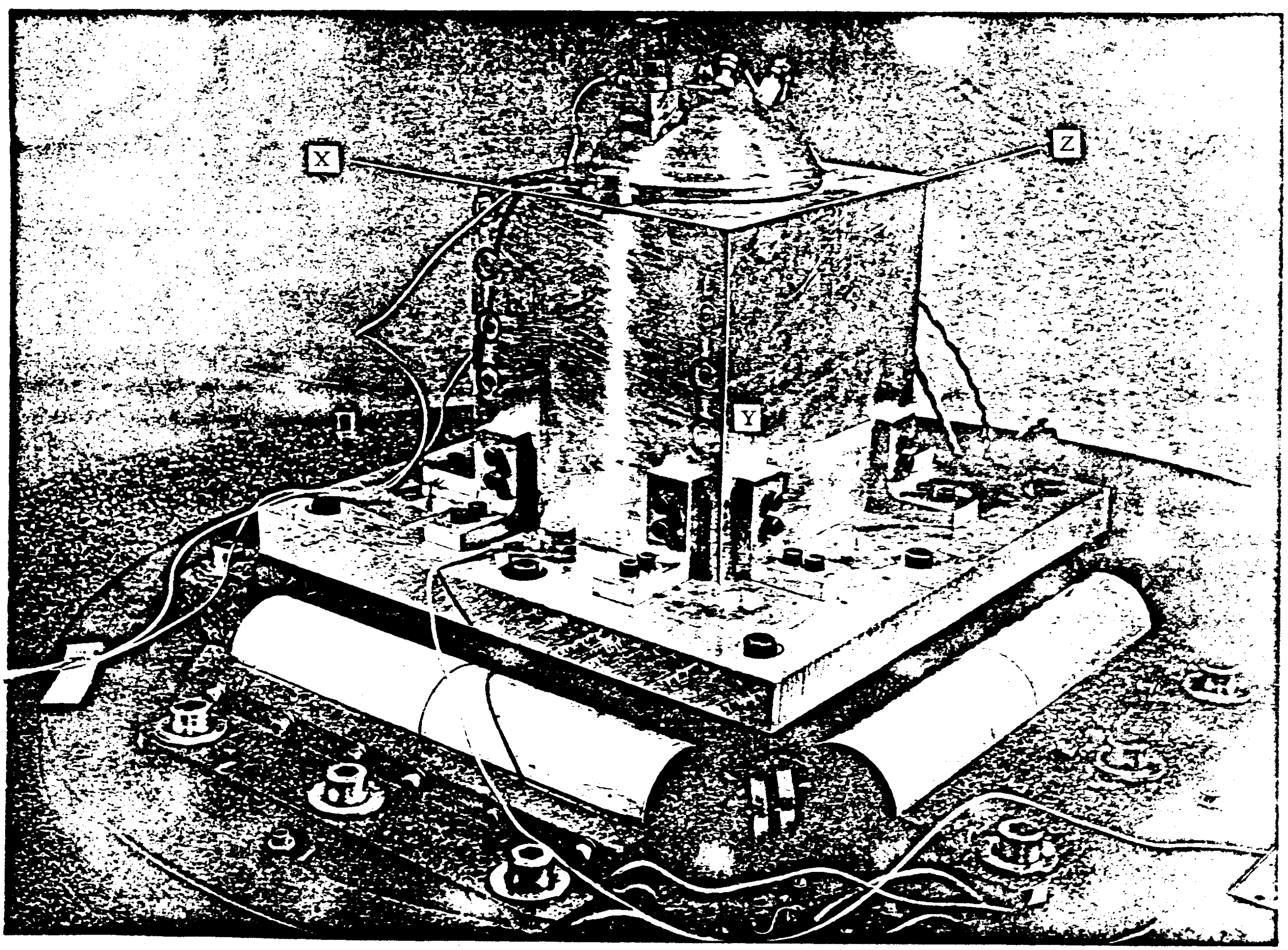

Fig. 13. Photograph of SNAP-III in Test Fixture

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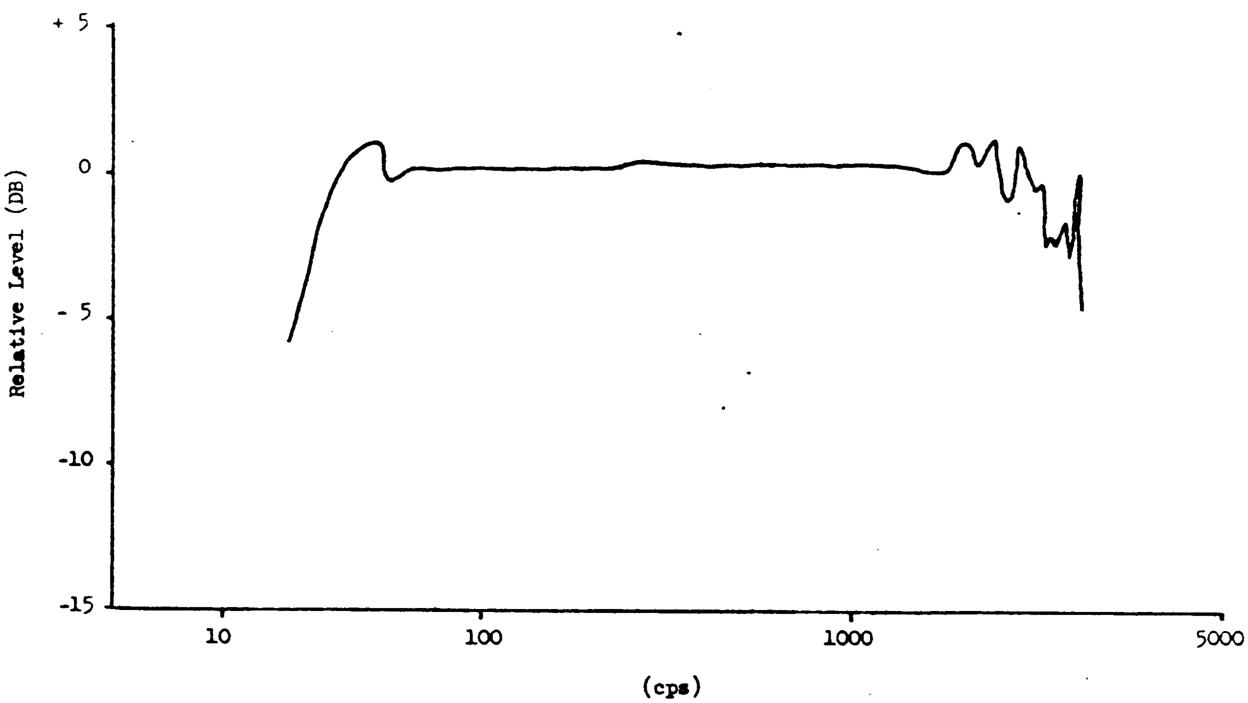

Fig. 14. Final Equalization Curve--Y Plane Model 177A Calidyne Shaker

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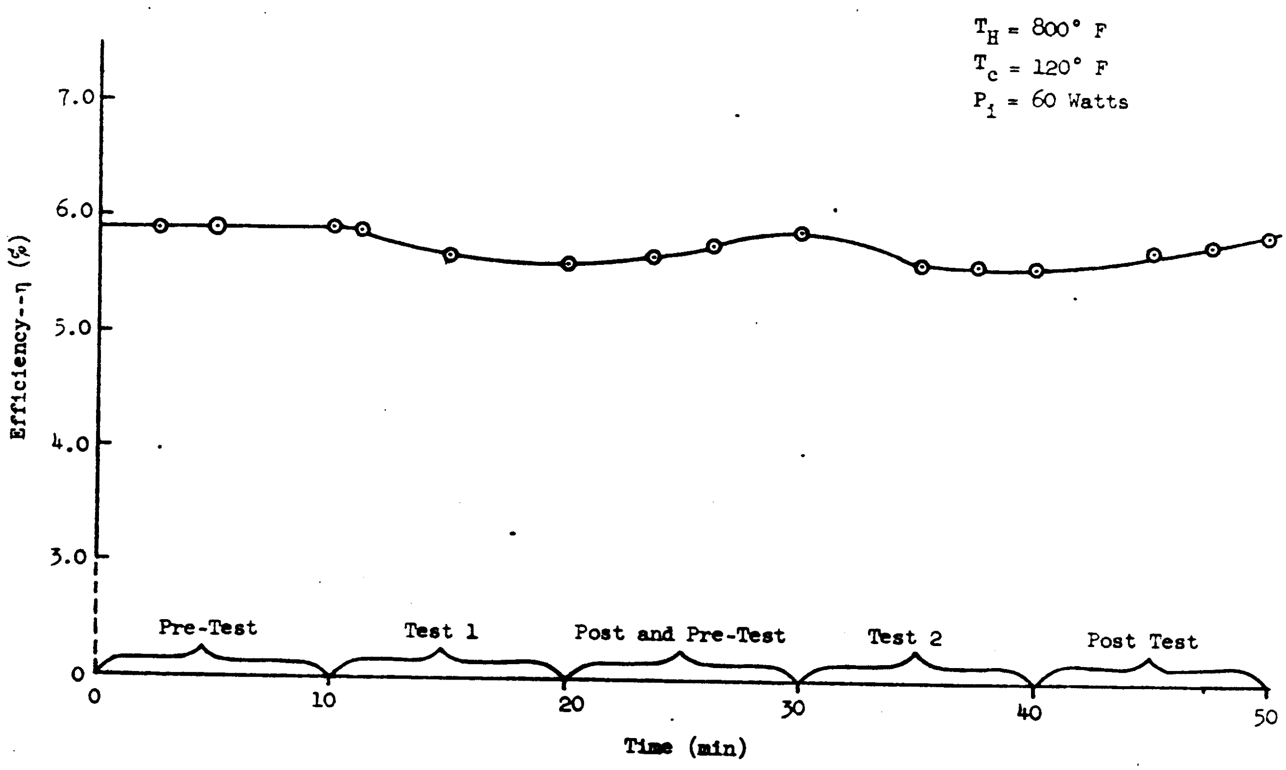

Fig. 15. Vibration Test SNAP-III Y Plane

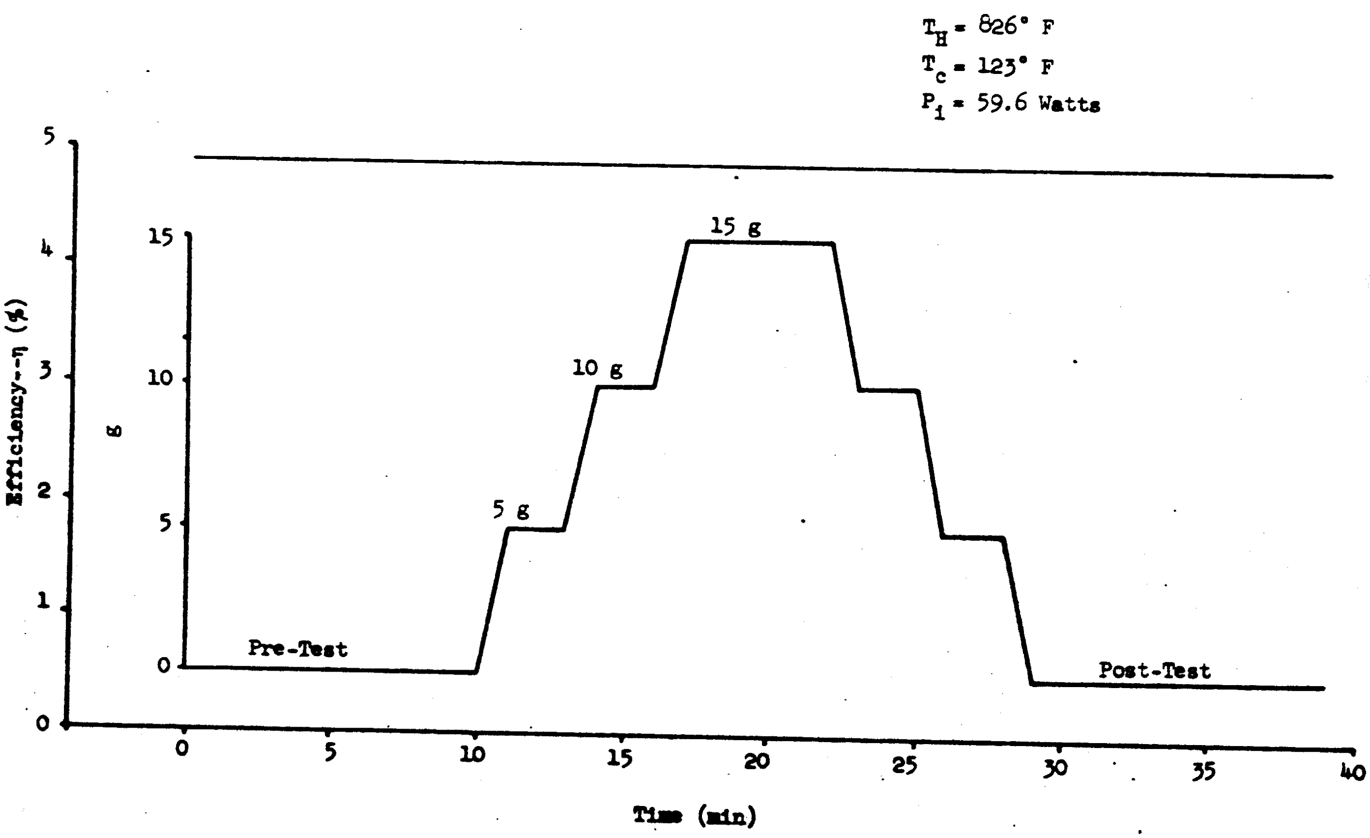

Fig. 16. Acceleration Test SNAP-III Y Plane

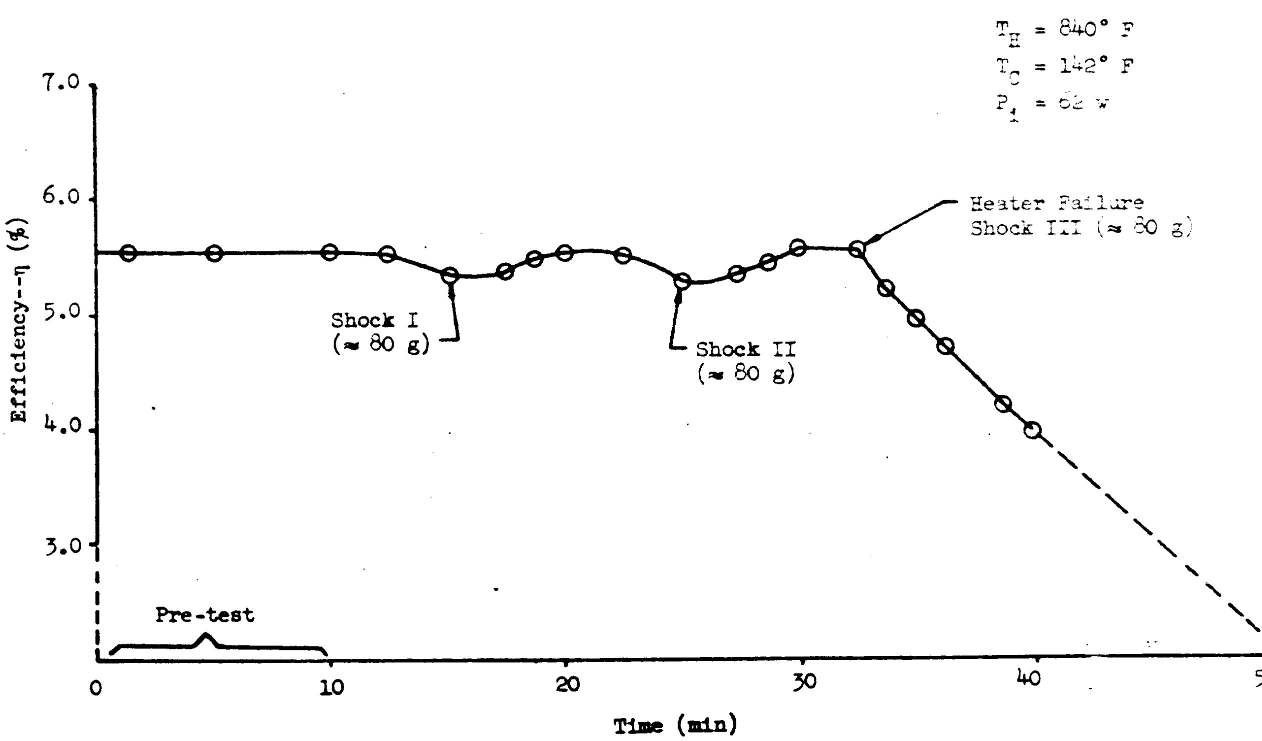

Fig. 17. Shock Test SNAP-III Y Plane